Theoretical motivation for EDM experiments: before and after the LHC

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Fermilab

Why go after EDMs?

Before anything else, searching for EDMs = probing the Abyss

You can try to pry out Nature's secrets with a sledgehammer (\$$10^9$ sledgehammer)

And you can take more subtle ways

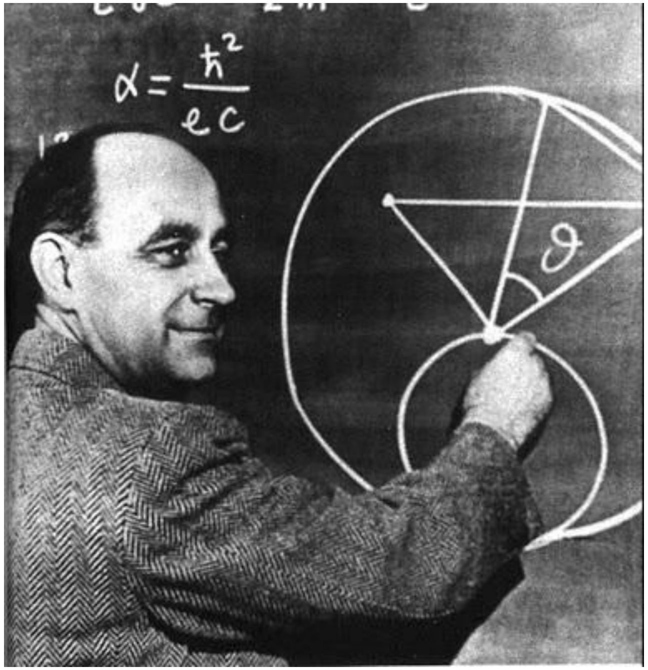
- These routs are complementary*
- A finite EDM will give *a scale*

$$i\left(\frac{em_f}{\Lambda^2}\right)\bar{f}\sigma^{\mu\nu}\gamma^5 f\,F_{\mu\nu}$$

* And if the subtle ways succeed, perhaps they'll get us an even bigger hammer

Why go after EDMs?

Previous man with an honest scale



•A finite EDM will give *a scale*

$$i\left(\frac{em_f}{\Lambda^2}\right)\bar{f}\sigma^{\mu\nu}\gamma^5 f\,F_{\mu\nu}$$

Why go after EDMs? *Before, during, and after LHC*

• **Electroweak scale**: little hierarchy - CP problem

EDMs and natural EWSB

Were no evidence for the MSSM, or indeed weak-scale SUSY, found at the LHC, would EDM experiments still be well-motivated?

• Baryon asymmetry: CPV in early Universe

BAU – EDM story: something ***big*** out there, but no scale a-priori…
Heart of Darkness

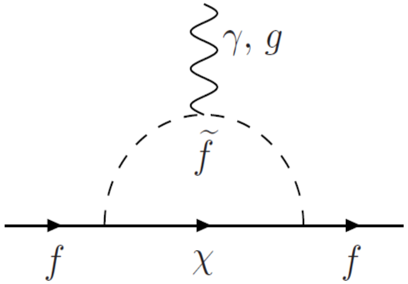
Some models rely on weak scale. Should see them!

Next generation EDM searches would be crucial for building a consistent story of *electroweak* baryogenesis

Electroweak scale: little hierarchy - CP problem

- *Game not over* for naturalness! May well still discover natural EWSB and then EDMs will be a cornerstone

- *May learn, instead,* that the weak scale is fine-tuned. If this happens, it won't *really* be a surprise
  … and EDMs would *truly* be at the forefront



➔ **EDM** experiments put pressure on natural SUSY long before LHC

➔ It's not future **EDM** experiments that will march on scorched ground in the aftermath of LHC; if anything,

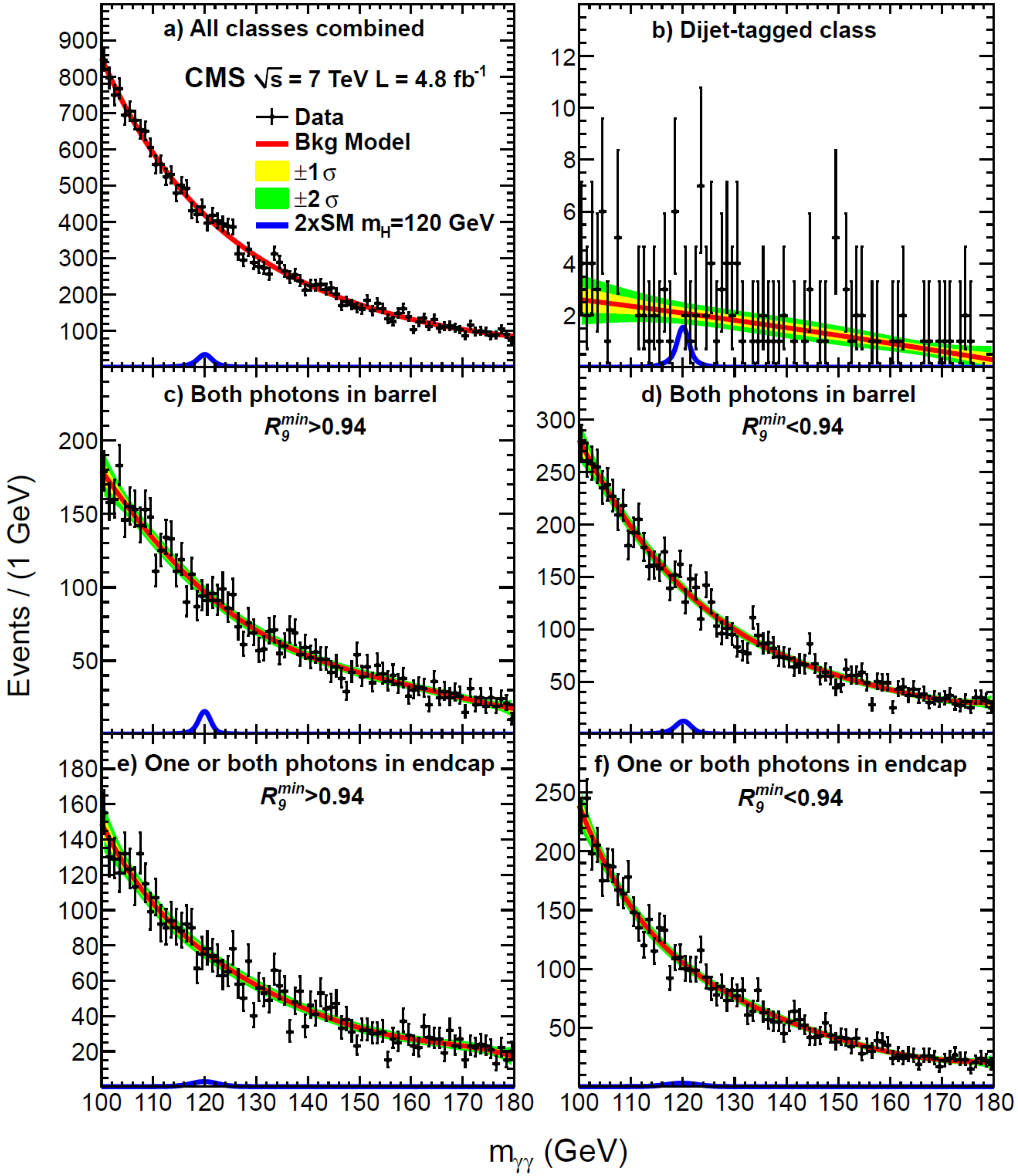
1. It's *LHC* that's eating the dust of current EDM constraints
2. EDMs are exciting with or without weak scale SUSY

The hint

I enjoy thinking that it's actually there

If it's there, now what?

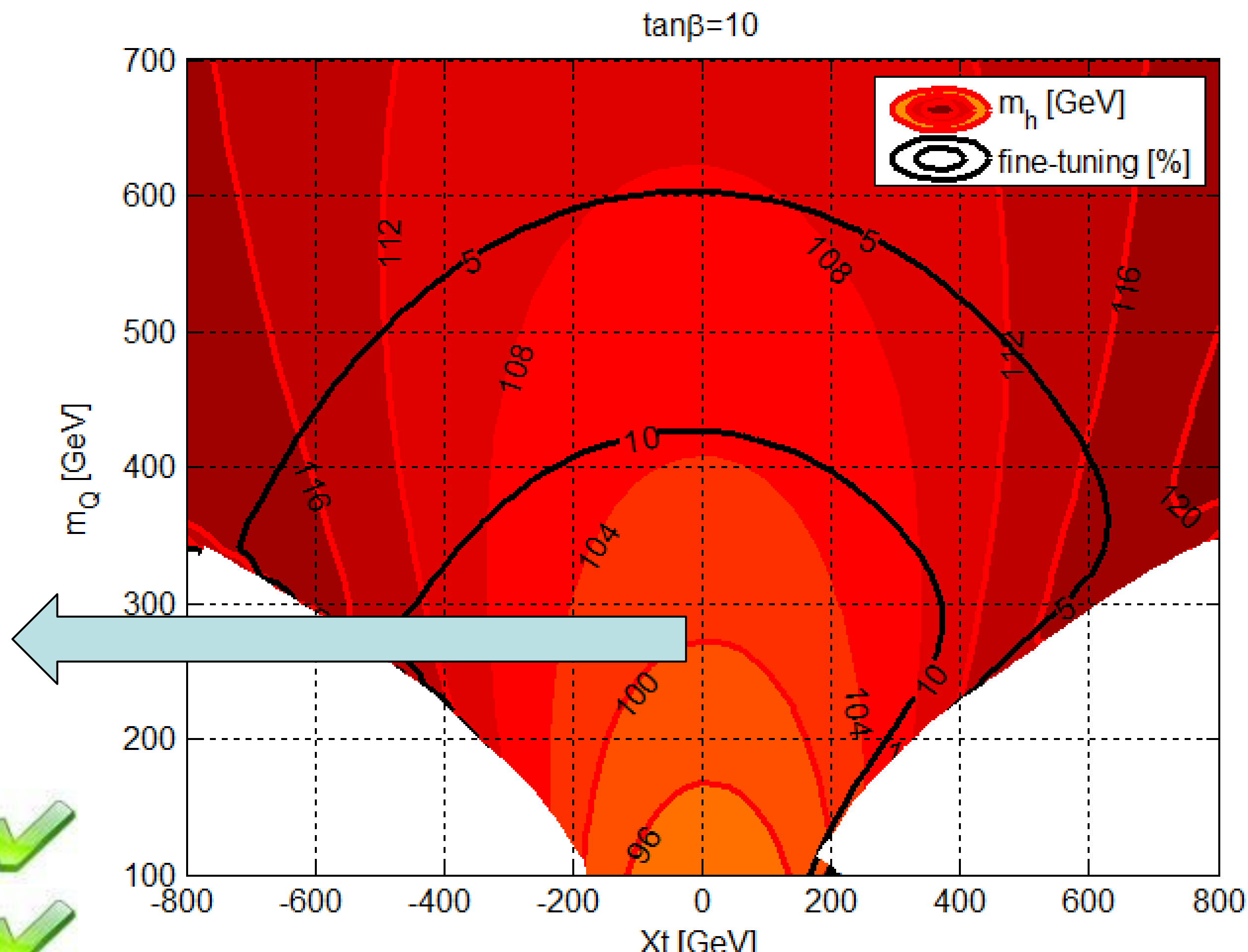
Is it alone or with friends?



Game not over for naturalness

- 125 GeV Higgs feels more like SUSY than most known alternatives
- **Natural SUSY ≠ minimal SUSY ➔ extended Higgs sector!**
  (MSSM Higgs sector curious since the beginning)

Top superpartners
Can be light!



Perfectly allowed
experimentally

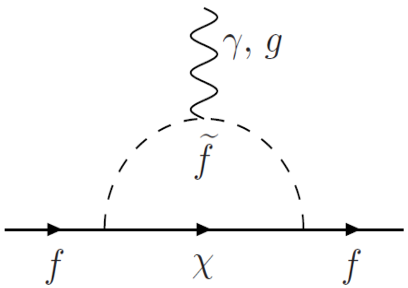
$b \to s\gamma \quad \frac{\Delta\rho}{\rho}$ ✔

LEP/Tevatron/LHC ✔

Game not over for naturalness

- **Natural SUSY ≠ minimal SUSY ➔ extended Higgs sector**

What does it mean for EDM searches?
First, recall usual implications of EDMs for weak scale SUSY



$$\arg\left(\langle H_u H_d \rangle M_2 \mu\right) = \mathcal{O}\left(10^{-2}\right)$$
$$\arg\left(A_f^* M_3\right) = \mathcal{O}\left(10^{-2}\right)$$

Conceivable with localized breaking of $U(1)_R$ $\quad B_\mu \sim \frac{g^2 \log \Lambda}{(4\pi)^2} M \mu, \quad A_f \sim \frac{Y_f g^2 \log \Lambda}{(4\pi)^2} M$

$$\langle H_u H_d \rangle \propto B_\mu^* \qquad \arg\left(\langle H_u H_d \rangle M \mu\right) = \arg\left(B_\mu^* M \mu\right) = 0$$

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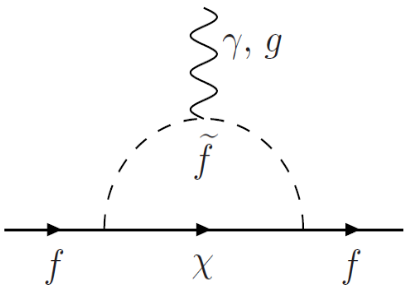

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Extended Higgs sector: $\cancel{\langle H_u H_d \rangle \propto B_\mu^*}$

Opportunity for EDMs!

Game not over for naturalness

- **Extended Higgs sector, opportunity for EDMs**

A minimal example

Breaks U(1)$_{R\text{-}PQ}$ softly in inert sector

$$\delta\mathcal{W} = \lambda S H_u H_d - \frac{M_S S^2}{2}$$

Supersymmetric version: M=700 GeV, λ=0.7 perturbative up to GUT

m_h=125 GeV with μ=200 GeV, stops @400 GeV

$$V \supset \left(B_\mu + \frac{\lambda^2 \mu^* v^2}{M_S} \right) H_u H_d + cc$$

$$\cancel{\langle H_u H_d \rangle \propto B_\mu^*} \qquad \Im\left(\langle H_u H_d \rangle M \mu\right) \approx -\left(B_\mu^* M \mu\right) \Im\left(\frac{\lambda^2 \mu^* v^2}{M_S B_\mu}\right)$$

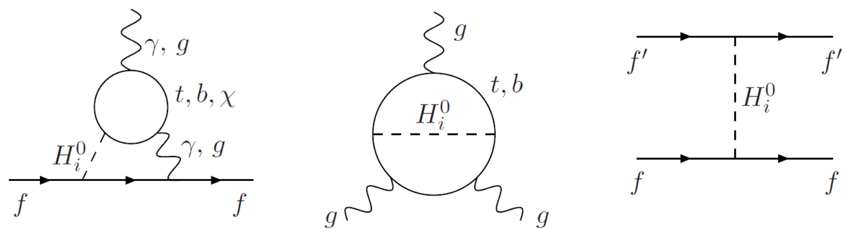
Phase suppressed by ~ O(0.1)

Around the corner for EDM searches

Game not over for naturalness

- **Extended Higgs sector, opportunity for EDMs**

Opportunity still there even if 1-2 gen' sfermions decouple



4F operators from Higgs exchange, down by Higgs & NP scales

$$M^2_{H_0} = \begin{pmatrix} m_h^2 & 0 & m_{hA}^2 \\ 0 & m_H^2 & m_{HA}^2 \\ m_{hA}^2 & m_{HA}^2 & m_A^2 \end{pmatrix} \qquad m_{hA}^2 \sim v^2 \arg\left(\frac{\lambda^2 \mu^* v^2}{M_S B_\mu}\right)$$

For m_A~300 GeV, already means phase ~ 10^{-2}, but decouples like m_A^{-2}
Next generation **EDM** search sensitive to Higgs @TeV

Game not over for naturalness

- **Extended Higgs sector, opportunity for EDMs**

Another possibility: EDMs could be telling us to look *down* – not up

Extended Higgs sector solves μ, μ-Bμ
Evade EDMs by *not* breaking $U(1)_{R\text{-}PQ}$ explicitly

$$\mathcal{W} = \lambda S H_u H_d + \frac{\kappa}{3} S^3$$

$$\mu = \lambda s \quad B\mu = \kappa^* \lambda s^{*2} + \frac{g^2 \lambda s}{16\pi^2} M$$

PNGB *eats our phase*

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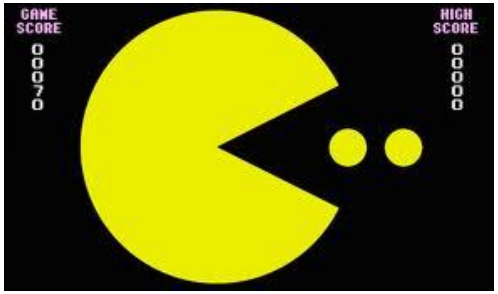
$$a \propto \arg\left(B\mu\right)$$

PNGB *eats our phase*

$$m_a^2 \propto \delta B\mu \sim \frac{g^2 \lambda s}{16\pi^2} M$$



•Exciting phenomenology
•Stay tuned to LHC for modified Higgs couplings

Should not fool **EDM** searches for long:
Next generation can find the two-loop residuals

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- Perhaps flavor, **EDM**s, meant all along that nothing is there @TeV

Were no evidence for the MSSM, or indeed weak-scale SUSY, found at the LHC, would EDM experiments still be well-motivated?

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Split supersymmetry: scalars ~100 TeV; gauginos / higgsinos ~TeV (dark matter)

Postpone understanding of little weak scale tuning
… get back to it as soon as we understand the cosmological constant

SUSY flavor and CP problems solved

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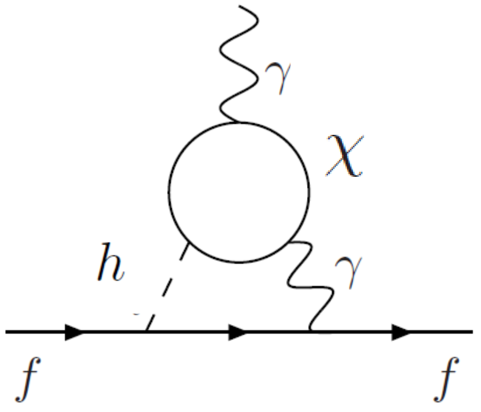
Split supersymmetry: scalars ~100 TeV; gauginos / higgsinos ~TeV

Weak scale EFT

$$-\mathcal{L} \supset \frac{M}{2}\lambda\lambda + \mu\tilde{h}_u\tilde{h}_d + \frac{g_u}{\sqrt{2}}h^*\tilde{h}_u\lambda + \frac{g_d}{\sqrt{2}}\tilde{h}_d h\lambda + cc$$

Contains a physical phase $\arg\left(g_u^* g_d^* v^2 M\mu\right)$



Two-loop EDMs in the ballpark of next gen' experiments

May well be our best hope in probing the next level

Baryon asymmetry: CPV in early Universe

When the Standard Model loses, it has the grace of losing by knock-out

With no one around to perform the experiment,
CPV occurs through very high-dimension operator

$$\Im \det \left[m_u m_u^\dagger, m_d m_d^\dagger \right]$$

B-violation above $T_{sphaleron}$~100 GeV

Extrapolating the CPV to the scale $T_{sphaleron}$, SM predicts an empty Universe.

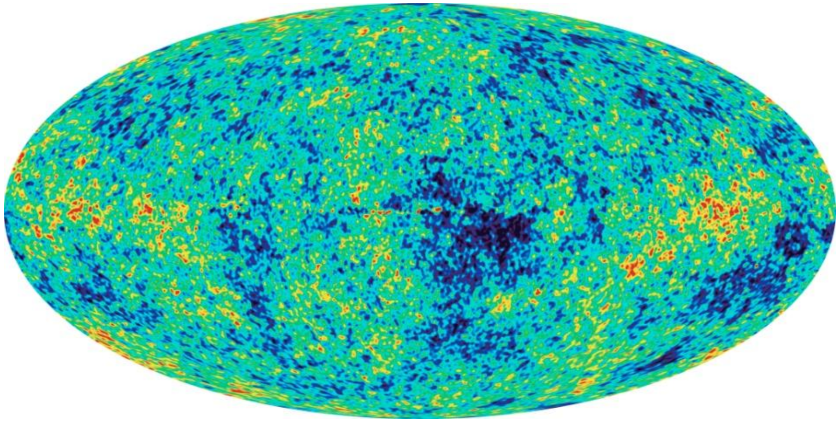
CPV ➔ QM ➔ problem cleanly at the hands of particle physicists
The holly grail in the quest for CP violation
Something BIG is out there

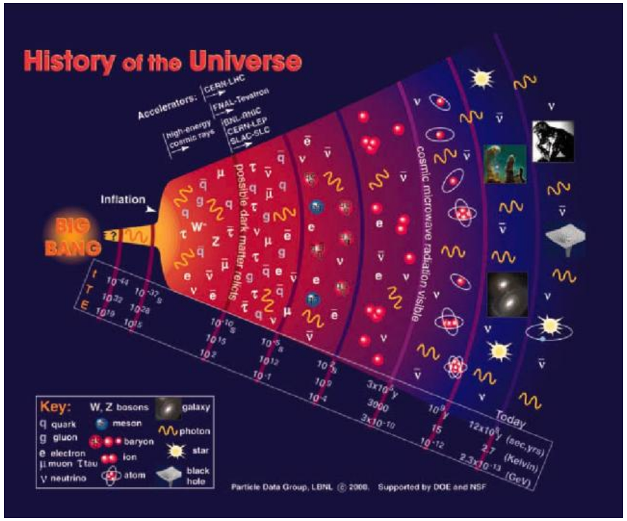
One little difficulty, that we should admit from the outset
…baryon asymmetry has no genuine scale.

1. B-L may be respected to arbitrarily high scale
2. Early Universe has been there to (almost) arbitrarily high scale

Lower limits on the BAU scale

$$Y_B = n_B/s = \begin{cases} (6.7 \; - \; 9.2) \times 10^{-11} & \text{BBN} \\ (8.36 \; - \; 9.32) \times 10^{-11} & \text{CMB} \end{cases}$$





Upper limit: reheating?

Solutions attached to every high scale we know that could comply with these limits

$\Lambda_{\text{electroweak}} = 100\,\text{GeV}$ $\quad\Lambda_{\text{seesaw}} = 10^{14}\,\text{GeV}$ $\quad\Lambda_{\text{GUT}} = 10^{16}\,\text{GeV}$

Electroweak Baryogenesis?

- Sakharov conditions: $\cancel{CP}$, $\cancel{B}$, $\cancel{TE}$

- Multistep calculation... Several No-Go's

  - 1st-order phase transition violates TE

    - Light, unscreened scalars coupled to H (stops?)
    - Extended Higgs sector

  - CPV currents

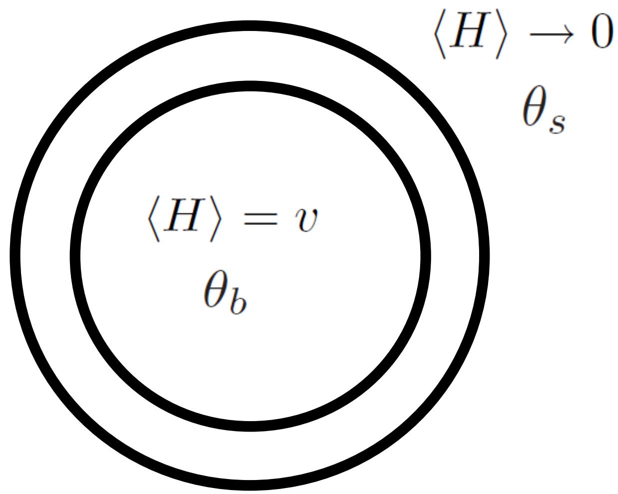
    - CPV sector can't be heavy; o.w. must be degenerate

  - Charge diffusion ahead of bubble wall

    - $\cancel{B}$ (via sphalerons) needs just the right amount of time to work
    - Depends on bubble properties (wall velocity) and on diffusion coefficients

CPV @ electroweak phase transition?

MSSM phases		BMSSM phases		vev phase
ϕ_i	ϕ_f	ϑ_1	ϑ_2	θ
$\arg(M_i\mu/b)$	$\arg(A_f\mu/b)$	$\arg(\epsilon_1/b)$	$\arg(\epsilon_2/b^2)$	$\arg(b\,H_u H_d)$



$\Delta\theta$ drives baryogenesis

$$\boxed{\Delta\theta \propto \theta}$$

$$\theta_b = \theta_s + \Delta\theta$$

$$M^2_{H_0} = \begin{pmatrix} m_h^2 & 0 & m_{hA}^2 \\ 0 & m_H^2 & m_{HA}^2 \\ m_{hA}^2 & m_{HA}^2 & m_A^2 \end{pmatrix}$$

$$m_{hA}^2 \propto \theta$$

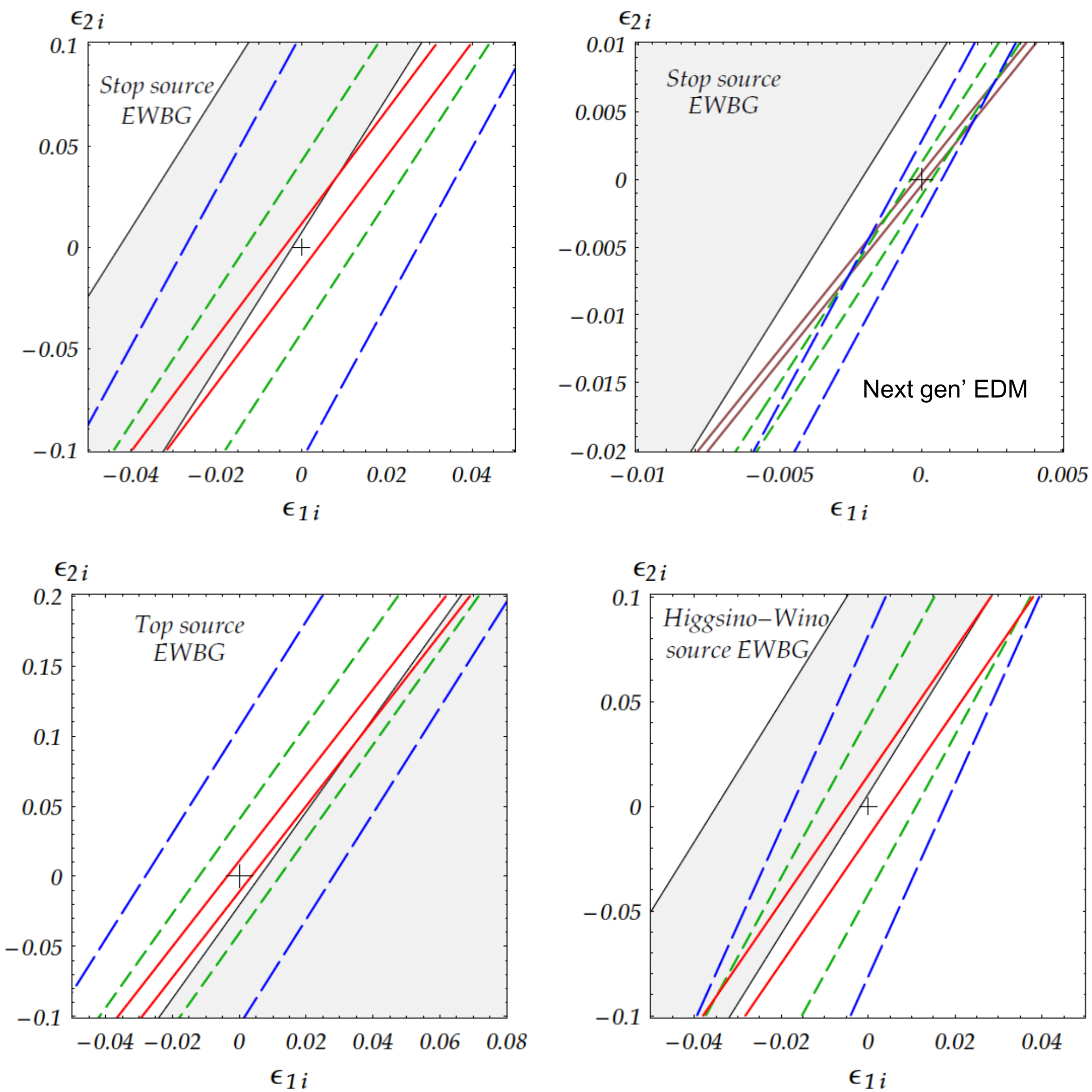
$$\boxed{\text{EDMs} \propto \theta}$$

Baryon asymmetry vs. EDM constraints

- EWBG and EDM constraints

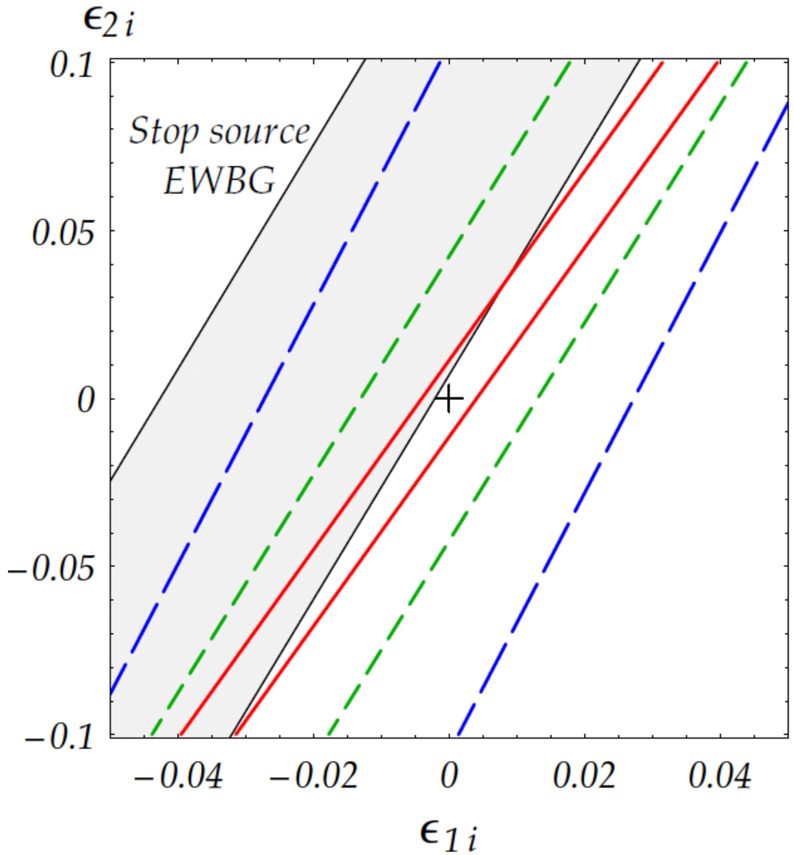
$$\boxed{\Delta\theta \propto \theta}$$

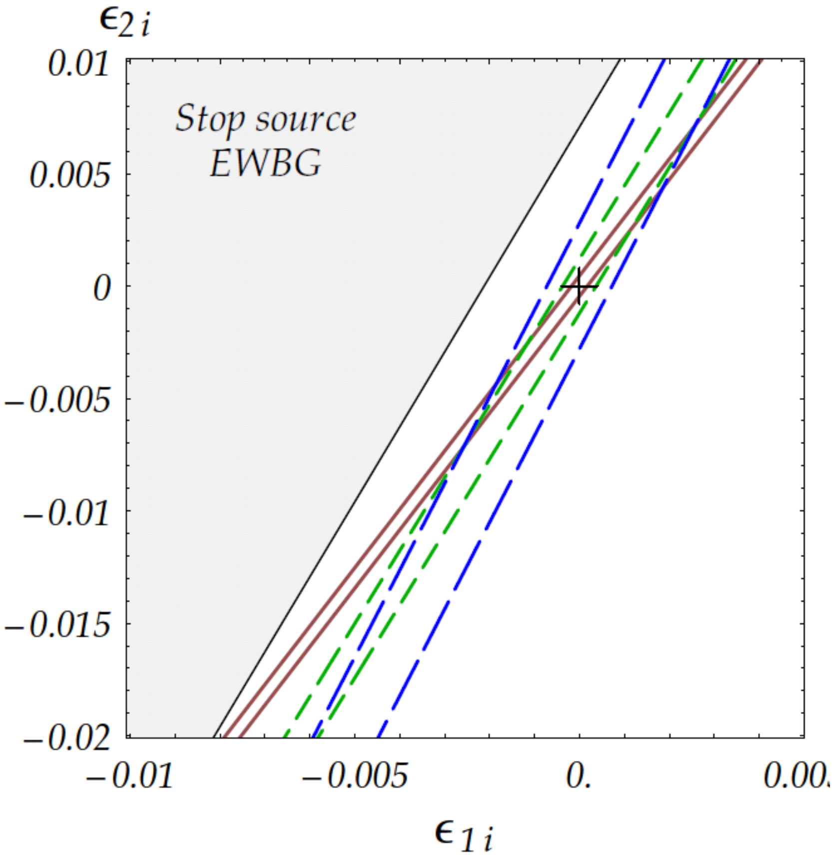
$$\boxed{\text{EDMs} \;\; \propto \theta}$$



Baryon asymmetry vs. upcoming EDM constraints

- EWBG and EDM constraints dependent
- No EDMs, no EWBG.





Why go after EDMs?

• **EDMs give a scale**

• **Electroweak scale**: little hierarchy - CP problem

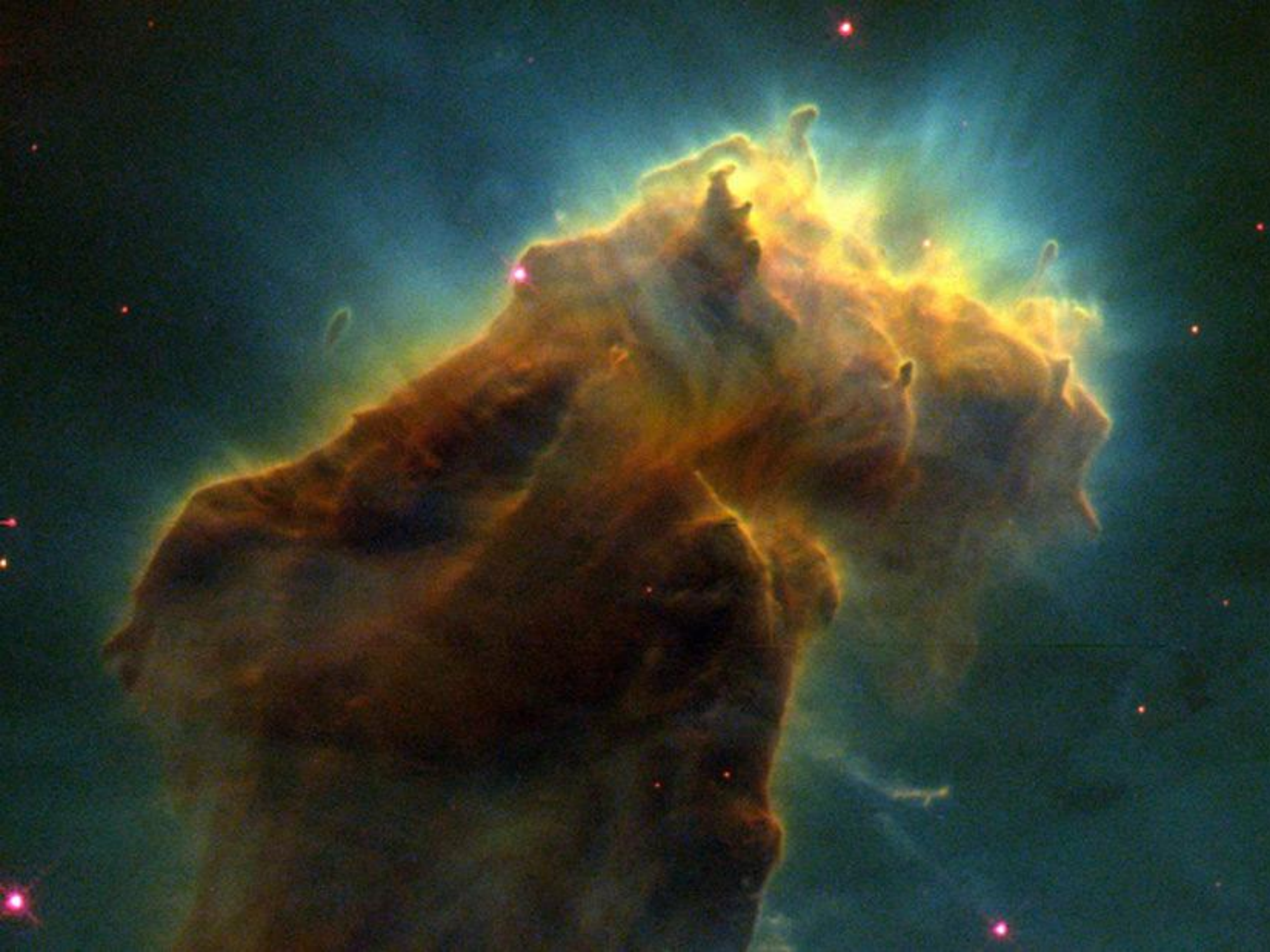
Very important if we find weak scale NP
Next hope if we don't

• Baryon asymmetry: CPV in early Universe

BAU – EDM story: something ***big*** out there, but no scale a-priori…
Heart of Darkness

Some models rely on weak scale. Should see them!

Next generation EDM searches would be crucial for building a consistent story of *electroweak* baryogenesis



F-term models

Generic prediction: O(20-100%) ***reduction* in hbb**

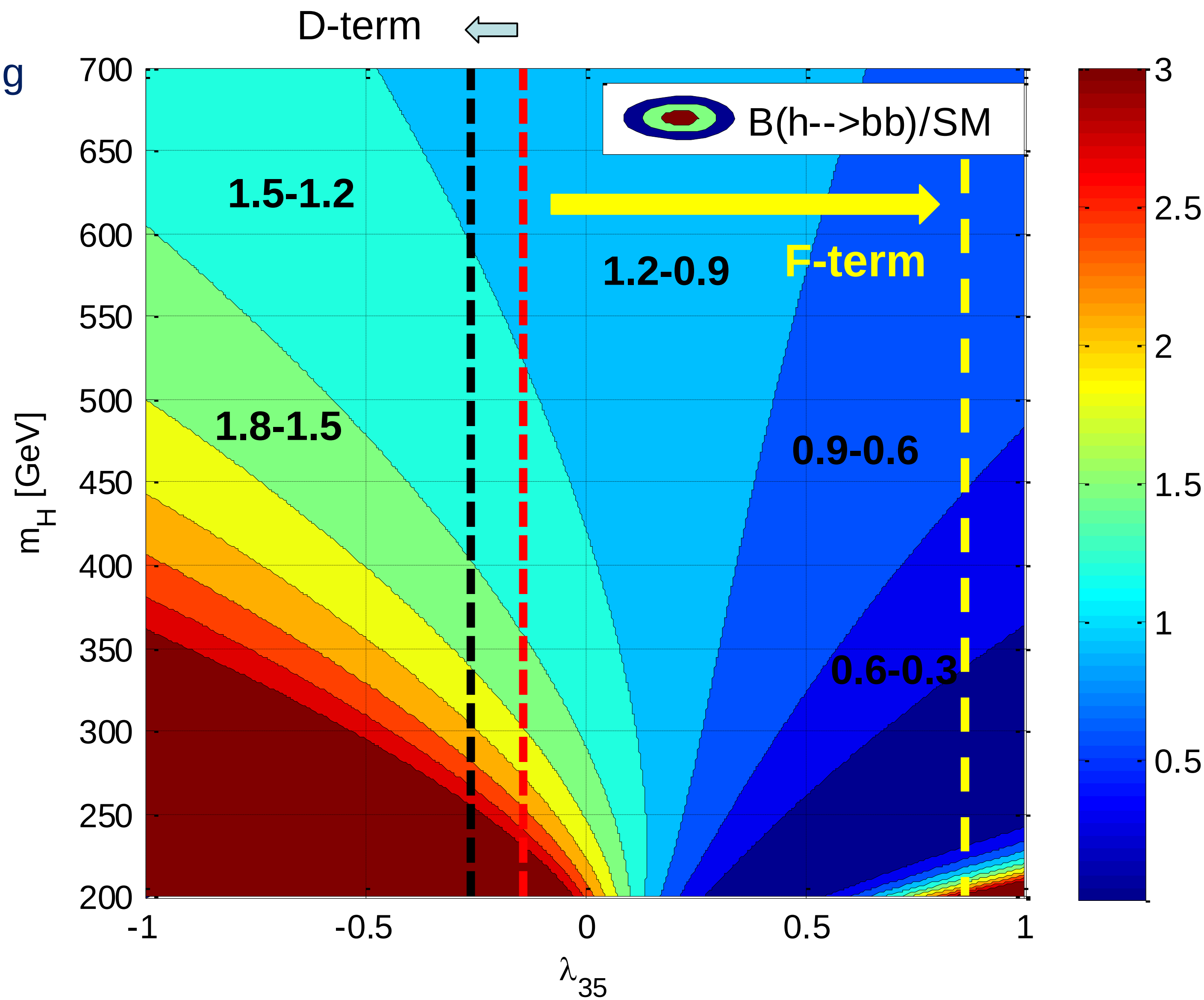
Caveats

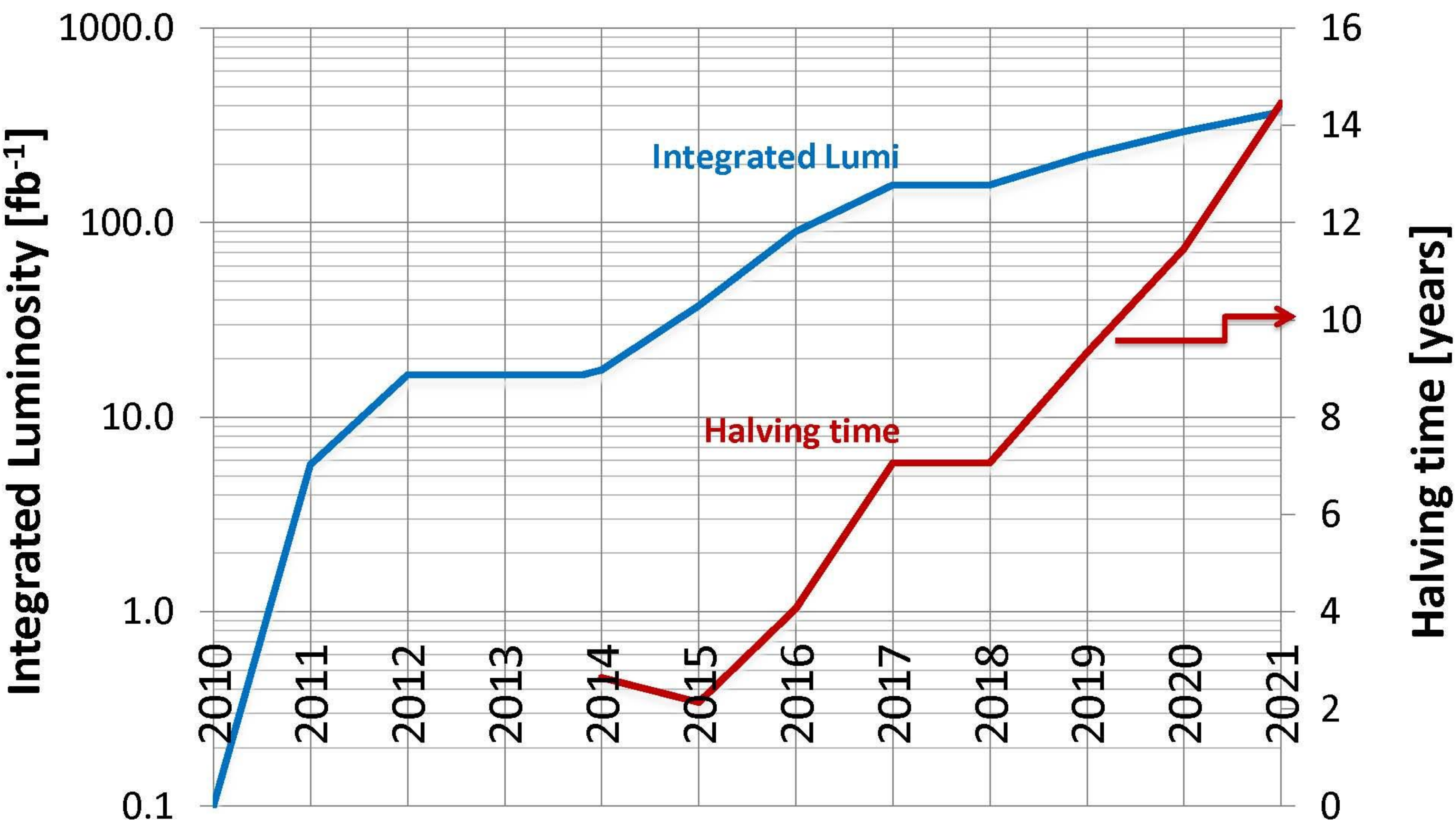
(i) Small doublet mixing limit not assured

(ii) Hard PQ-breaking easily larger effect for large m_H

(iii) Singlet-doublet mixing

Somewhat more involved than pure D-term case





Credit: Frank Zimmermann
(Modified from O. Brüning, M. Lamont, L. Rossi)

CPV currents

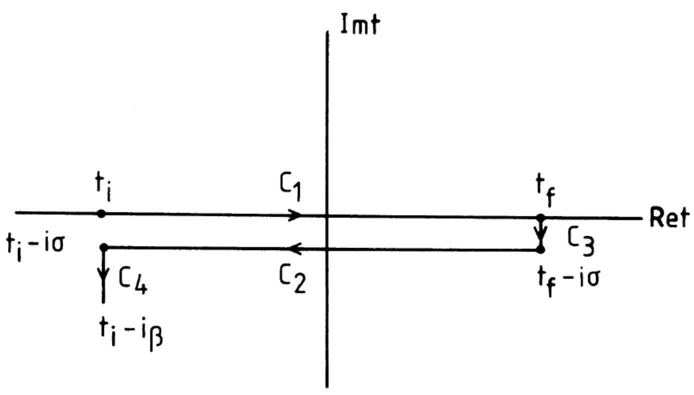
• Disagreements in literature, qualitative and quantitative (~ order of magnitude)

Recently, e.g., Cline & Kainulainen (‘00), Carena et al (‘01-2), Konstandin et al (‘05), Cirigliano et al (’04-9), Chung et al (’09)

• When in doubt, take a simple path.
Follow Riotto (‘98) (later Cirigliano et al (’05-9))

• Estimated BAU somewhat higher than other approaches.
Good for us: eventually, formulate conditions to rule out EWBG in BMSSM

Real time formalism (Closed Time Path: amounts to ending the contour back at t_i)



$$G^>(x,y) = \langle \phi_-(x)\phi_+^\dagger(y)\rangle$$
$$G^<(x,y) = \langle \phi_-^\dagger(y)\phi_+(x)\rangle$$
$$G^t(x,y) = \langle T\{\phi_+(x)\phi_+(y)\}\rangle = \theta(x_0-y_0)G^>(x,y) + \theta(y_0-x_0)G^<(x,y)$$
$$G^{\bar{t}}(x,y) = \langle T\{\phi_-(x)\phi_-^\dagger(y)\}\rangle = \theta(x_0-y_0)G^<(x,y) + \theta(y_0-x_0)G^>(x,y)$$

CPV currents

Riotto (1998)

- Simple perturbative derivation from Schwinger-Dyson equation

$$G = G^0 + G^0 \, \Sigma \, G$$

Pack Green's function on both CTP branches in economic way (similar for self energy),

$$\widetilde{G}(x,y) = \begin{pmatrix} G^t(x,y) & -G^<(x,y) \\ G^>(x,y) & -G^{\bar{t}}(x,y) \end{pmatrix}$$

Express SDE in two ways (make products explicit)

$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z \; \widetilde{G}^0(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}(z,y)$$
$$\widetilde{G}(x,y) = \widetilde{G}^0(x,y) + \int d^4w \int d^4z \; \widetilde{G}(x,w)\widetilde{\Sigma}(w,z)\widetilde{G}^0(z,y)$$

Non-interacting eom give

$$\left(\Box_x + m^2\right) \widetilde{G}(x,y) = -i\delta^{(4)}(x-y) - i \int d^4z \; \widetilde{\Sigma}(x,z)\widetilde{G}(z,y)$$
$$\left(\Box_y + m^2\right) \widetilde{G}(x,y) = -i\delta^{(4)}(x-y) - i \int d^4z \; \widetilde{G}(x,z)\widetilde{\Sigma}(z,y)$$

- Now find CPV current perturbatively

$$\lim_{x \to y} (\partial_\mu^x - \partial_\mu^y) G^<(x,y) = -i j_\mu(X)$$

CPV currents

Macroscopic vs. microscopic coordinates $X = (T, \vec{X}) = \frac{1}{2}(x+y), \quad (t, \vec{r}) = x - y$

Obtain: $$\frac{\partial n}{\partial X_0} + \boldsymbol{\nabla} \cdot \mathbf{j}(X) = \int d^3 z \int_{-\infty}^{X_0} dz_0 \Big[\Sigma^>(X,z) G^<(z,X) - G^>(X,z)\Sigma^<(z,X) + G^<(X,z)\Sigma^>(z,X) - \Sigma^<(X,z) G^>(z,X) \Big]$$

- Diffusion approximation $\nabla j = -D \nabla^2 n$
- Need to compute scattering term $S_{\tilde{t}_R}(X) = S^{CP}_{\tilde{t}_R}(X) + S^{CPV}_{\tilde{t}_R}(X)$

Expand in VEV: use (dressed) equilibrium Green's function

$$G^\lambda(x,y) = \int \frac{d^4 k}{(2\pi)^4} e^{-ik\cdot(x-y)} g_B^\lambda(k_0, \mu_i)\rho(k_0, \mathbf{k})$$

$$g_B^>(\omega, \mu) = 1 + n_B(\omega - \mu_i)$$
$$g_B^<(\omega, \mu) = n_B(\omega - \mu_i)\,,$$

$$n_B(x) = 1/(e^{x/T} - 1)$$

$$\rho(k_0, \mathbf{k}) = \frac{i}{2\omega_k}\left[\left(\frac{1}{k_0 - \omega_k + i\epsilon} - \frac{1}{k_0 + \omega_k + i\epsilon}\right) - \left(\frac{1}{k_0 - \omega_k - i\epsilon} - \frac{1}{k_0 + \omega_k - i\epsilon}\right)\right]$$

- Compute self-energy perturbatively

CPV currents

• Example: stops $\mathcal{L} \supset -y_t \tilde{t}_L \tilde{t}_R^* [A_t v_u(x) - \mu^* v_d^*(x)] + cc$

$$\Sigma_{\tilde{t}_R}(x,y) = -g(x,y) G_{\tilde{t}_L}(x,y),$$
$$\Sigma_{\tilde{t}_L}(x,y) = -g^*(x,y) G_{\tilde{t}_R}(x,y) \qquad g(x,y) = y_t^2 [A_t v_u(x) - \mu^* v_d^*(x)][A_t^* v_u^*(y) - \mu v_d(y)]$$

A relaxation term and a source term:

$$S_{\tilde{t}_R}^{CP}(X) = -\int d^3x \int_{-\infty}^{T} dt\, [g(X,x) + g(x,X)]\, \mathcal{R}e \left[G_{\tilde{t}_L}^{>}(X,x) G_{\tilde{t}_R}^{<}(x,X) - G_{\tilde{t}_L}^{<}(X,x) G_{\tilde{t}_R}^{>}(x,X) \right]$$
$$S_{\tilde{t}_R}^{CPV}(X) = -i \int d^3x \int_{-\infty}^{T} dt\, [g(X,x) - g(x,X)]\, \mathcal{I}m \left[G_{\tilde{t}_L}^{>}(X,x) G_{\tilde{t}_R}^{<}(x,X) - G_{\tilde{t}_L}^{<}(X,x) G_{\tilde{t}_R}^{>}(x,X) \right]$$

$$\begin{aligned} S_{\tilde{q}_R}^{\not{C}\not{P}} &= -\, S_{\tilde{q}_L}^{\not{C}\not{P}} \\ &= \frac{3 y_q^2 K_{\tilde{q}}(z)}{2\pi^2} \int_0^\infty \frac{k^2\, dk}{\omega_{\tilde{q}_L}\, \omega_{\tilde{q}_R}}\, \mathrm{Im} \left[\frac{n_B(\mathcal{E}_{\tilde{q}_R}^*) - n_B(\mathcal{E}_{\tilde{q}_L})}{(\mathcal{E}_{\tilde{q}_L} - \mathcal{E}_{\tilde{q}_R}^*)^2} + \frac{1 + n_B(\mathcal{E}_{\tilde{q}_R}) + n_B(\mathcal{E}_{\tilde{q}_L})}{(\mathcal{E}_{\tilde{q}_L} + \mathcal{E}_{\tilde{q}_R})^2} \right] \end{aligned}$$

• Phase space integral and $\dot{\beta}$ term same as in MSSM. But additional $\dot{\theta}$ contribution

$$\boxed{\begin{aligned} K_{\tilde{q}}(z) &= |A_q\, \mu|\; v^2(z)\, \dot{\beta}(z)\; \sin\left(\phi_q + \theta(z)\right) \\ &+ \frac{v^2(z)}{4} \left(s_{4\beta}\; |A_q\, \mu|\; \cos\left(\phi_q + \theta(z)\right) + s_{2\beta}^2\; \left(|\mu|^2 - |A_t|^2\right) \right)\; \dot{\theta}(z) \end{aligned}}$$

Diffusion of charge near bubble wall

- Diffusion of chiral charge $$\partial_t n_a - D_a \nabla^2 n_a = \sum_b \Gamma_{ab} n_b + S_a^{\not{CP}}$$
- Available time for charge to distribute ahead of wall $\tau_{\rm diff} = \bar{D}/v_w^2$
- Two extreme regimes are bad for EWBG:
  - $\Gamma_{\rm ws} \gg \tau_{\rm diff}^{-1}$ sphalerons erase BAU before swept up by bubble
  - $\Gamma_{\rm ws} \ll \tau_{\rm diff}^{-1}$ sphalerons have no time to convert chiral charge

Optimal scenario: $\Gamma_{\rm ws} \sim \tau_{\rm diff}^{-1}$

Corresponds to $v_w \sim \sqrt{\bar{D}\Gamma_{\rm ws}} \sim ({\rm few}) \times 10^{-2}$

→ Fast wall is bad. Velocity known within ~ order of magnitude, $0.01 < v_w < 0.4$

changes BAU by factor 4-5

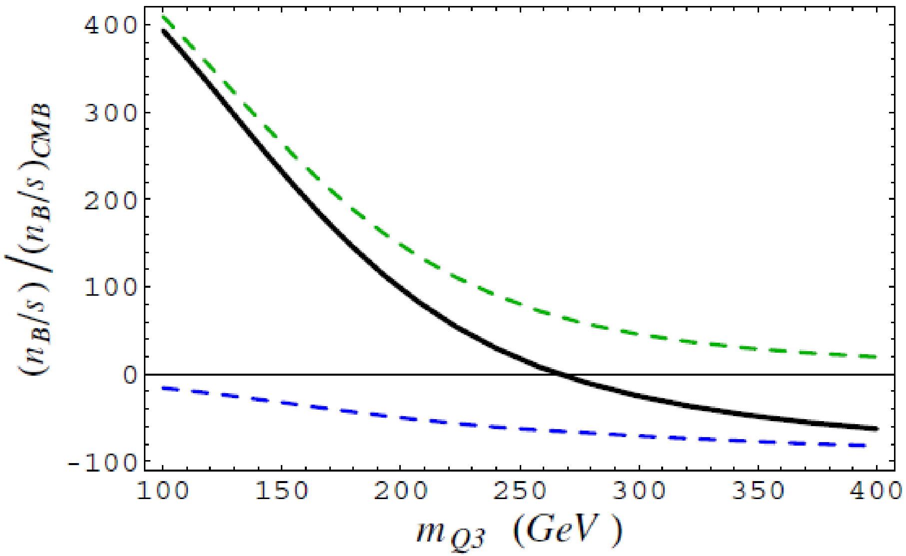
Produced baryon asymmetry

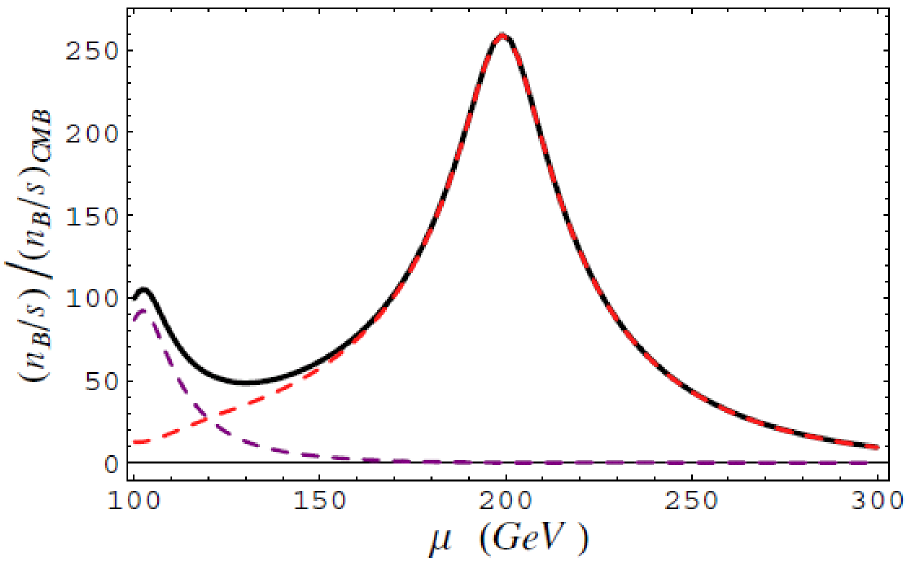
BMSSM vs. MSSM:

- New sources: top and stops. Stop source efficient

- Important: new BMSSM sources $\dot{\theta} \sim \Delta\theta \propto \theta$, limited by EDMs to ~ 10^{-2}.
  But, does not require additional CPV

- In contrast, usual MSSM sources $\dot{\beta} \sim \Delta\beta$ ~ 10^{-2},
  and also require CPV limited by EDMs to ~ 10^{-2}





MSSM EWBG is (very) nearly ruled out

MSSM EWBG requires VERY light stop
Restricted (in addition to EDMs) by cosmology, direct detection, colliders